Semi Annual Report

(July 1 — December 31, 2003)

Contract Number NAS5—31363

OCEAN OBSERVATIONS WITH EOS/MODIS:

Algorithm Development and Post Launch Studies

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Preamble

This document describes our progress thus far toward completion of our research plans regarding two MODIS Ocean-related algorithms.

A. Retrieval of the Normalized Water-Leaving Radiance (Atmospheric Correction).
B. Retrieval of the Detached Coccolith/Calcite Concentration

In addition, we break our effort into two broad components for each algorithm:

- Algorithm Improvement/Enhancement;

- Validation of MODIS Algorithms and Products.

These components will overlap in some instances.

RETREIVAL OF NORMALIZED WATER-LEAVING RADIANCE (ATMOSPHERIC CORRECTION)

Algorithm Improvement/Enhancement

1. Evaluation/Tuning of Algorithm Performance

Task Progress:

We have worked closely with R. Evans' group to try to resolve various calibration issues with MODIS. In addition, we participated in the MODIS calibration workshop in August (Voss in person, Gordon via teleconference).

Anticipated Future Actions:

We will continue to work on validation of the atmospheric correction algorithms on Terra and Aqua.

2. and 3. Algorithm Enhancements

There are two important issues we are examining for inclusion into the MODIS algorithm: effecting atmospheric correction in the presence of strongly absorbing aerosols and/or Case 2 waters; and including the influence of the subsurface upwelling BRDF on water-leaving radiance.

Strongly Absorbing Aerosols/Case 2 waters

The first of the two enhancements we have been considering concerns absorbing aerosols. It also concerns Case 2 (coastal) waters, as strongly absorbing aerosols can be expected near the coasts due to urban pollution. Although success with SeaWiFS has shown that the MODIS algorithm performs well in ~ 90% of Case 1 water situations, it does not perform adequately everywhere; most notably in atmospheres containing strongly absorbing aerosols, or in turbid coastal waters that have high concentrations of all optically active constituents. Two important situations in which absorbing aerosols make an impact are desert dust and urban pollution carried over the oceans by the winds. In the case of urban pollution the aerosol contains black carbon and usually exhibits absorption that is nonselective, i.e., the imaginary part of the refractive index (the absorption index) is independent of wavelength. In contrast, desert dust absorbs more in the blue than the red, i.e., the absorption index decreases with wavelength. Generally, analysis of imagery contaminated by strongly absorbing aerosols require that atmospheric correction and water-constituent retrieval be carried out simultaneously. The same is true for Case 2 coastal waters. Because of the similarity of the algorithm requirements, we treat absorbing aerosols and Case 2 waters together.

Task Progress:

Previously, we applied (and validated) the spectral optimization algorithm [R.M. Chomko and H.R. Gordon, Atmospheric correction of ocean color imagery: Test of the spectral optimization algorithm (SOA) with SeaWiFS, *Applied Optics*, **40**, 2973—2984, 2001] with the Garver and Siegel reflectance model ["Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation: 1 time series from the Sargasso Sea," *Geophys. Res.*, **102C**, 18607—18625, 1997] in Case 1 waters. The results have now been published [R.M. Chomko, H. R. Gordon, S. Maritorena, D.A. Siegel, Simultaneous retrieval of oceanic and atmospheric parameters for ocean color imagery by spectral optimization: A validation, *Remote Sensing of Environment* **84,** 208—220, 2003]. We are now applying the spectral optimization algorithm to Case 2 waters and are trying to validate it for these waters using SeaWiFS data.

Our application of the Case 2 version of the algorithm SeaWiFS imagery over coastal waters has led to inconsistent results □ the algorithm performs very well on some imagery and poorly on others. This behavior is shown in the set of SeaWiFS imagery following Figure 1. These were all processed with the Case 2 version of the SOA using the Garver and Siegel water reflectance model (as optimized for Case 1 waters and validated by Chomko *et al*. [2003]). In what follows we shall refer to the individual figures by referencing their year and day of the year, i.e., "1997-279" means day 279 of year 1997.

Figure 1997-279 shows an example of an excellent processing result. This was a member of the image set that Chomko *et al*. [2003] used to validate the SOA in Case 1 waters. Note the good consistency of the atmospheric properties $\square_0$ and □ as one moves from the open ocean to the coast, particularly in the Pamlico Sound area. Also, there are no obvious water features in the retrieved atmospheric parameters. There is no indication of algorithm failure anywhere in the image. In contrast, Figure 1998-267 shows a large area with a Chlorophyll *a* concentration (C) of 0.02 mg/m^3 (purple color on the figure). This value of C is one of the starting values used in the optimization, and the result suggests that at these point the optimization did not vary C at all (or at most very little). In other words, the algorithm failed at these points. The failure seems to be associated with high values of a_{cdm}, although the retrieved values are no higher than those in Figure 1997-279. However, note the values of a_{cdm} in Figure 1998-267 are probably bogus because the algorithm failed. Another indication of the failure is the total inconsistency of the atmospheric properties $\square_0$ and □ as one moves from the open ocean to the coast, particularly in the Pamlico Sound area.

Figure 1998-287 shows only a small region where the processing failed and good consistency of the atmospheric properties $\square_0$ and □ as one moves from the open ocean to the coast, particularly in the Pamlico Sound area, while Figure 1999-279 shows a larger region of failure and poor consistency of atmospheric parameters. The area of failure is even larger in Figure 1999-300. Conversely, Figure 2000-129 shows what would appear

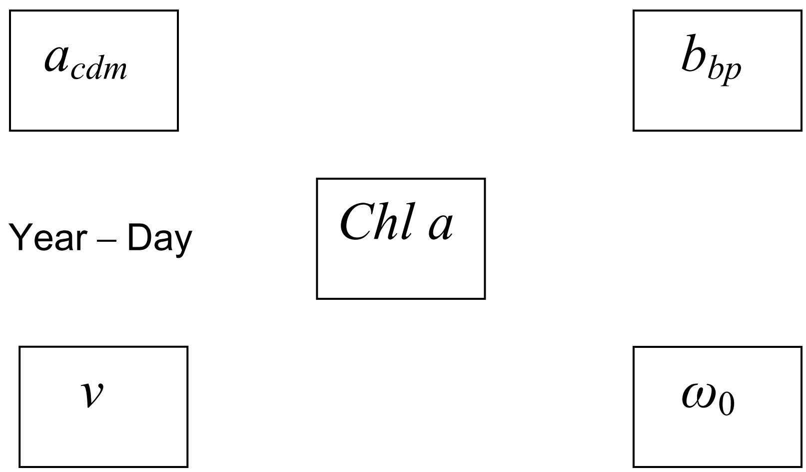
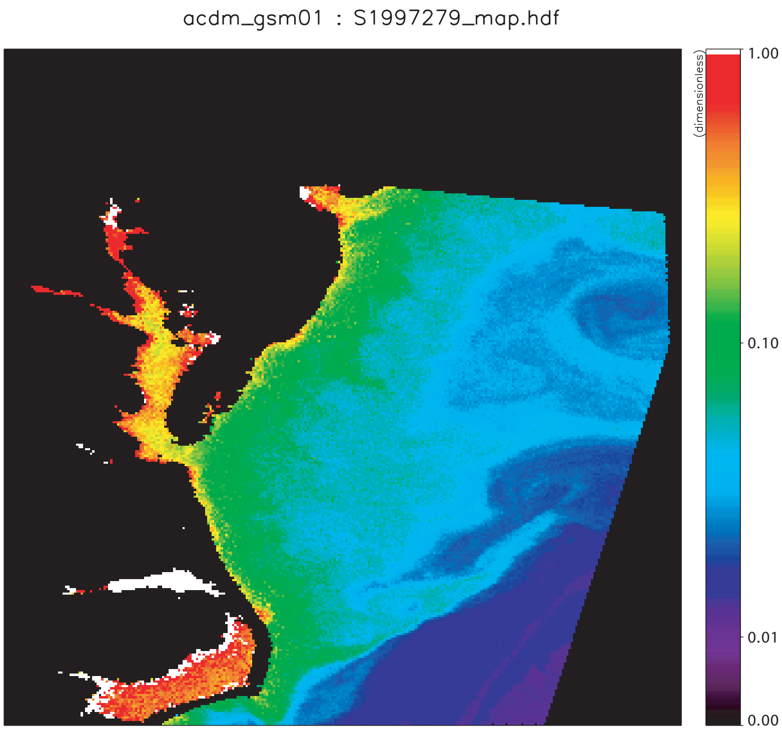


Figure 1. The following Case 2 figures all have the layout shown above.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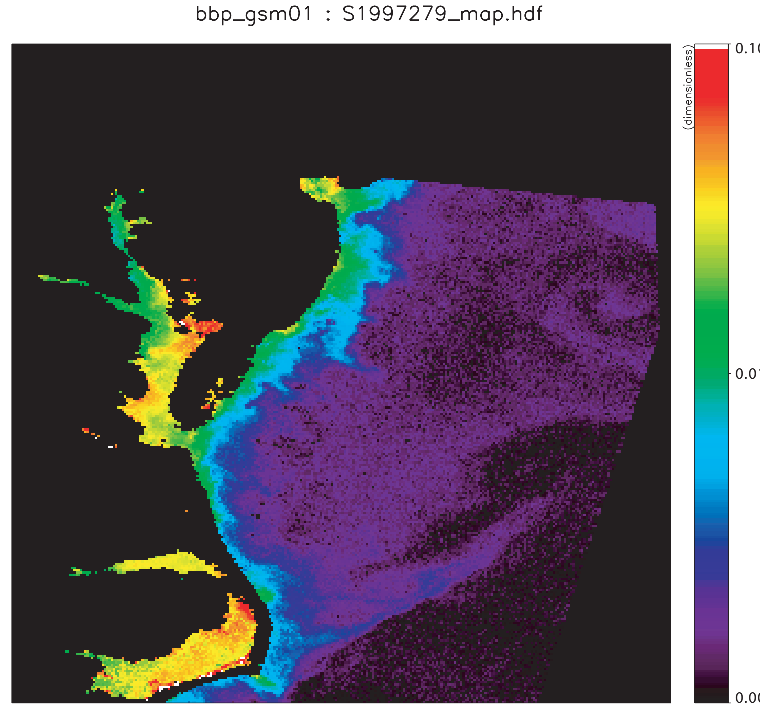
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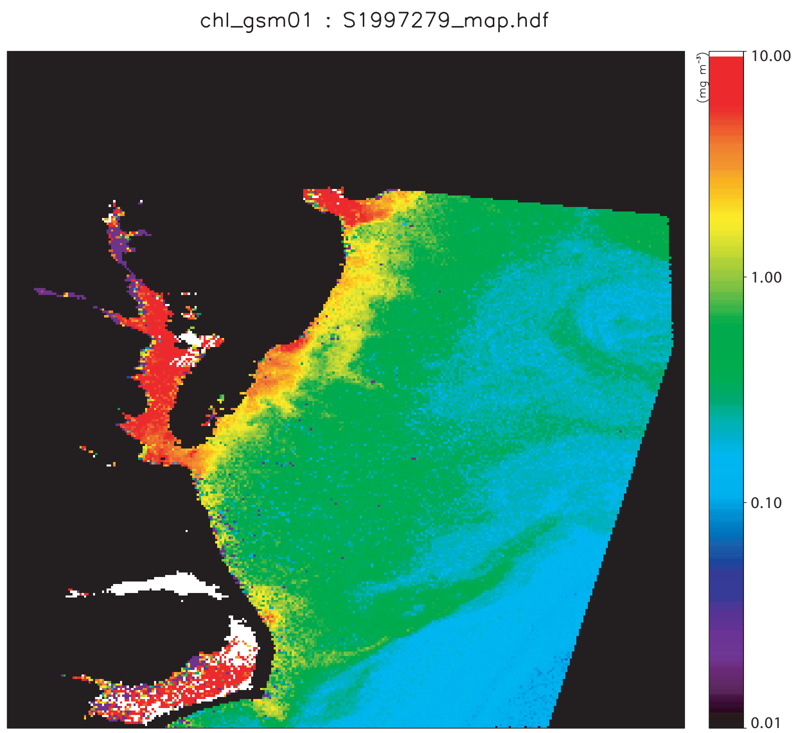
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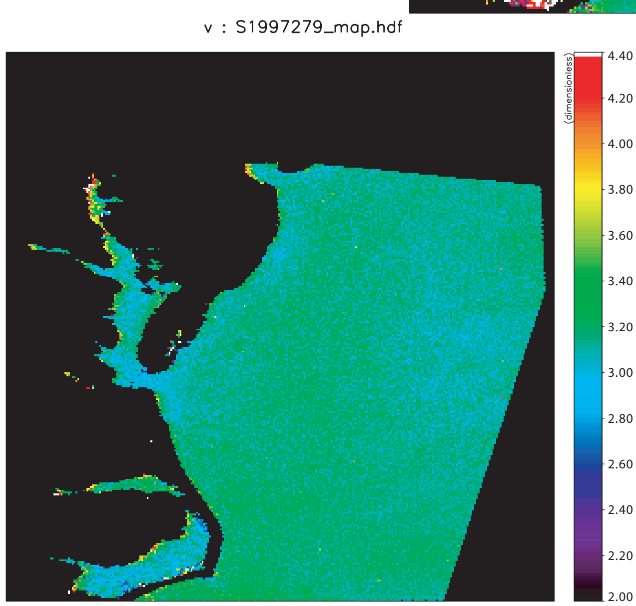
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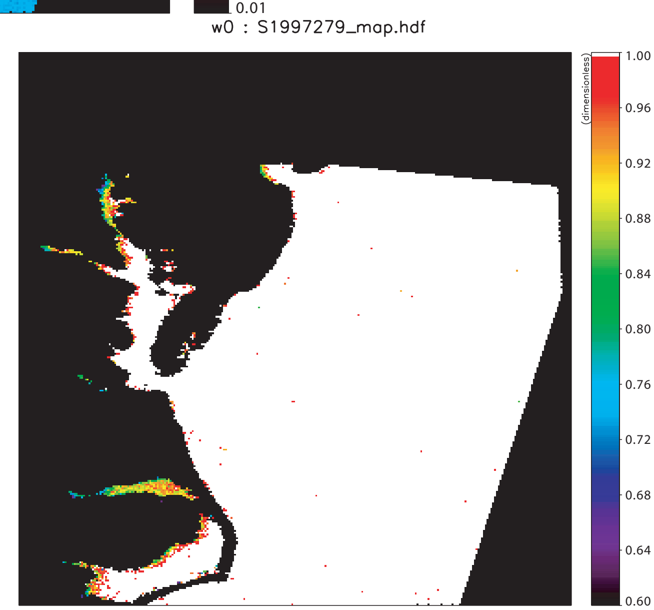
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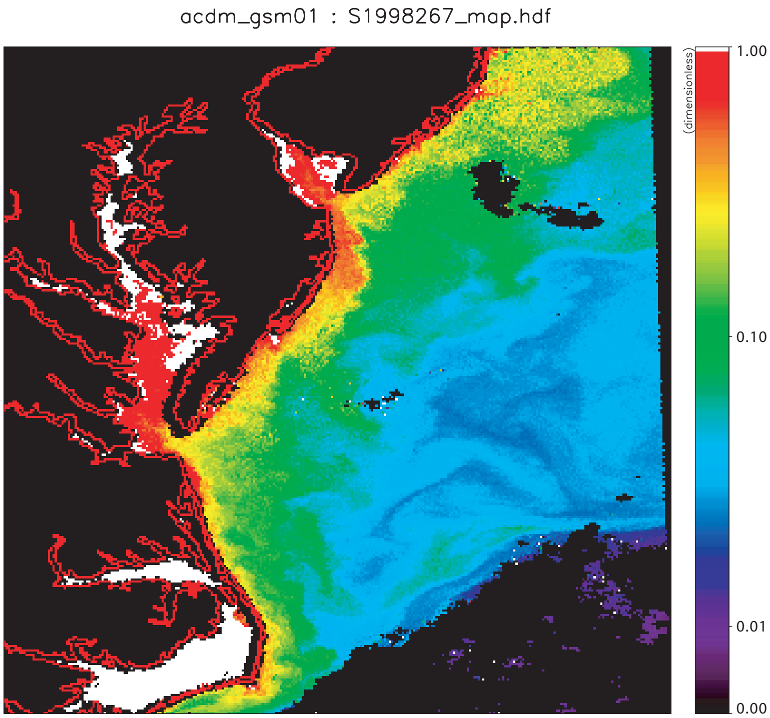
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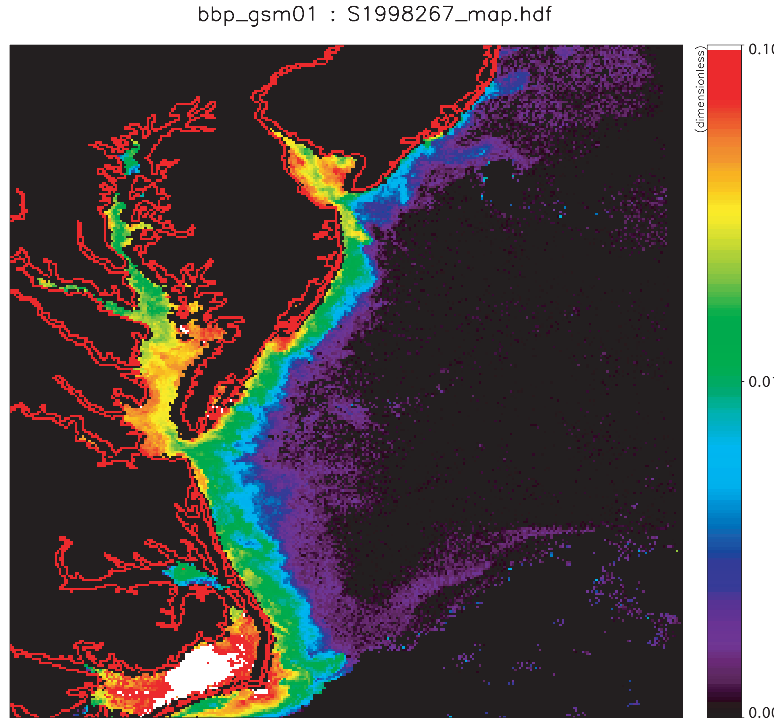
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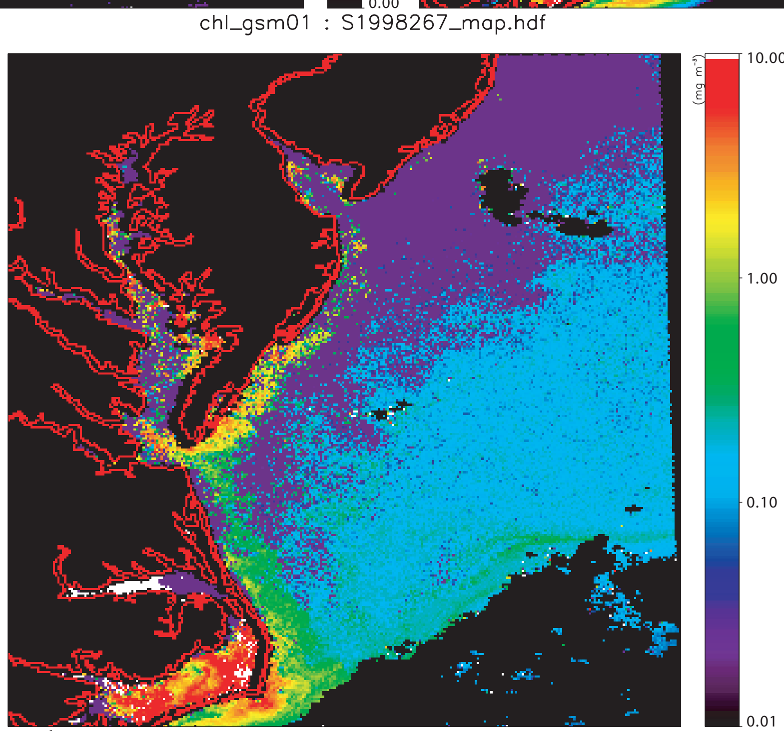
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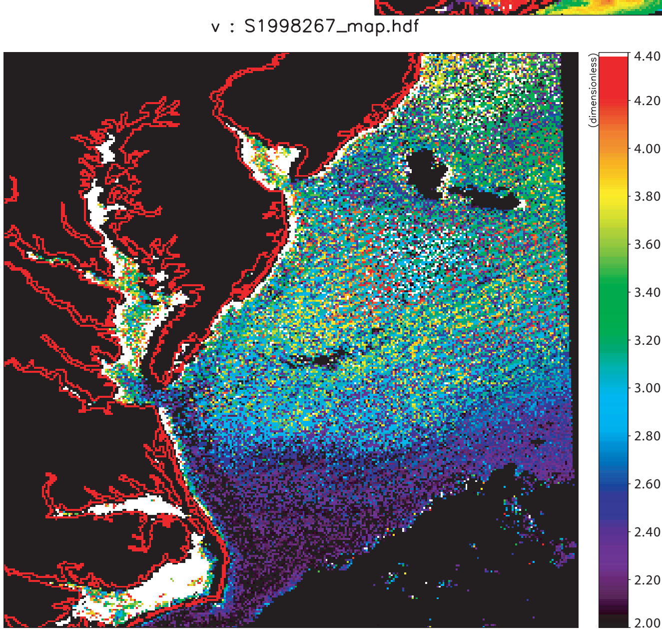
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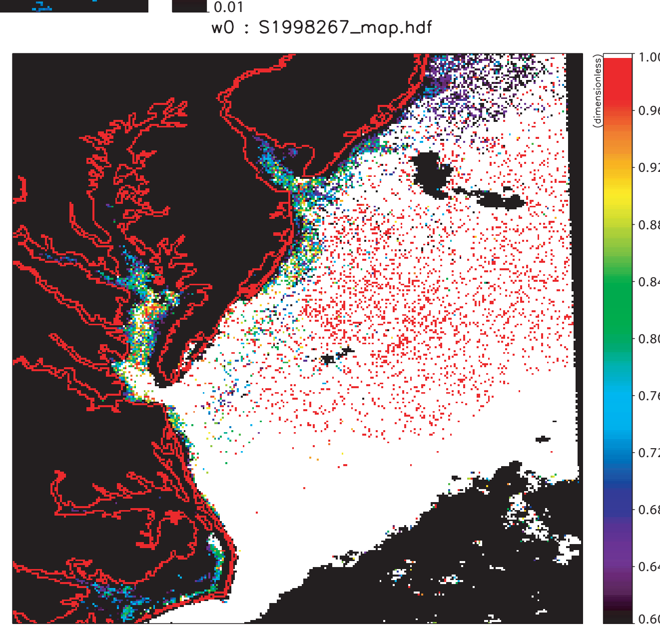
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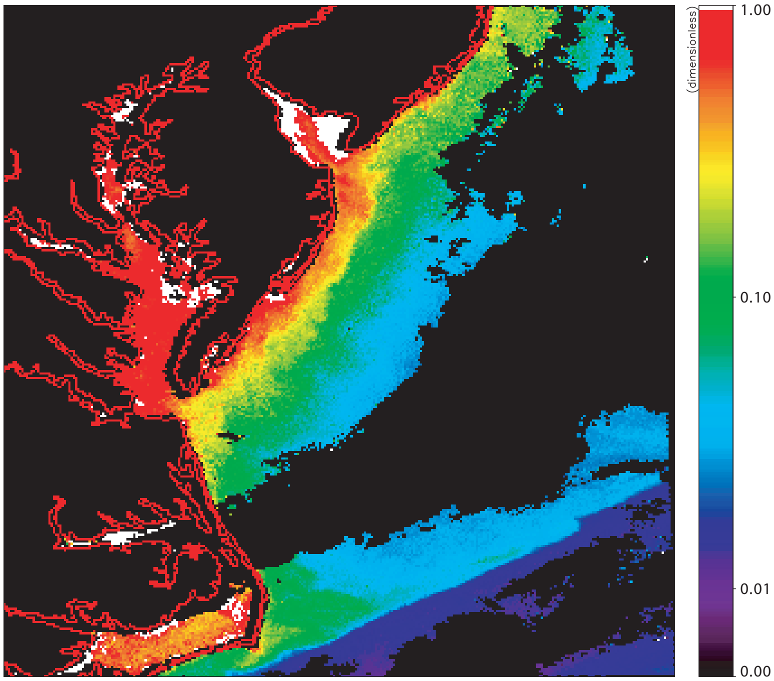

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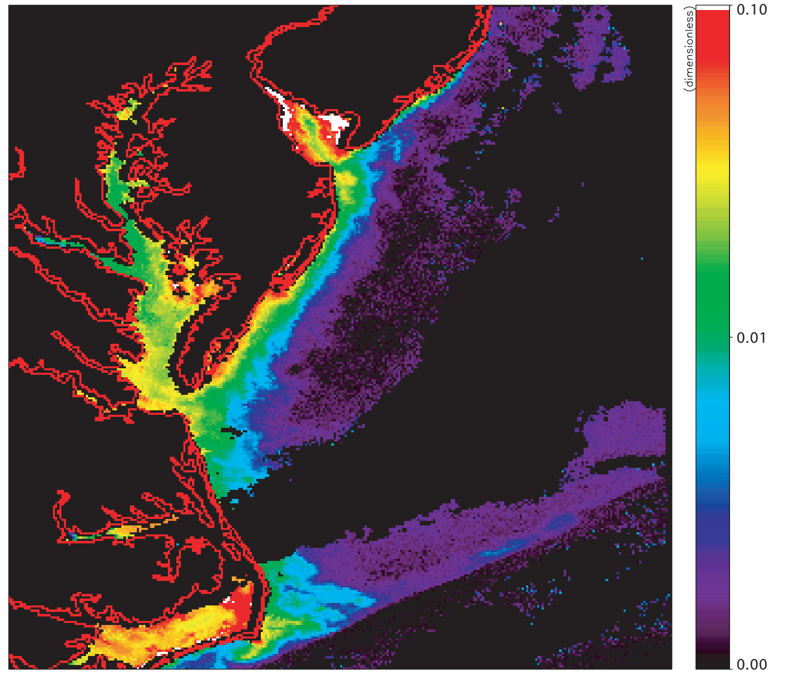

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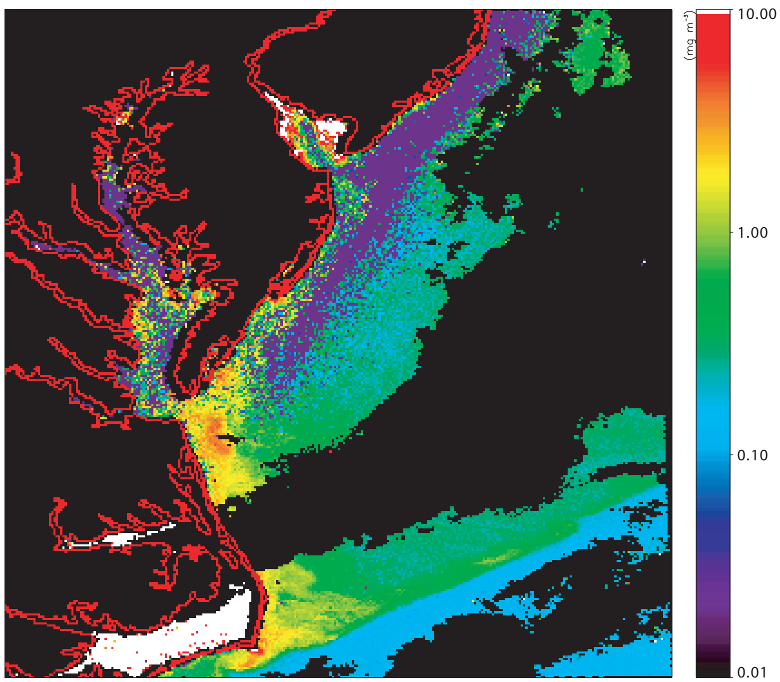

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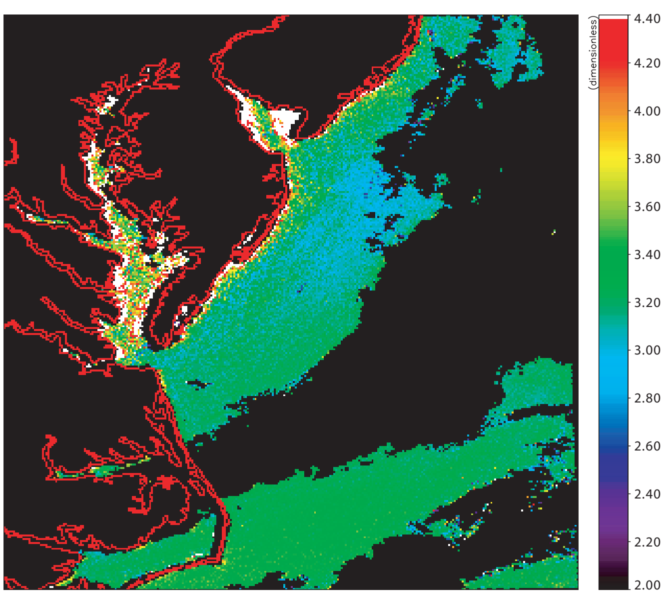

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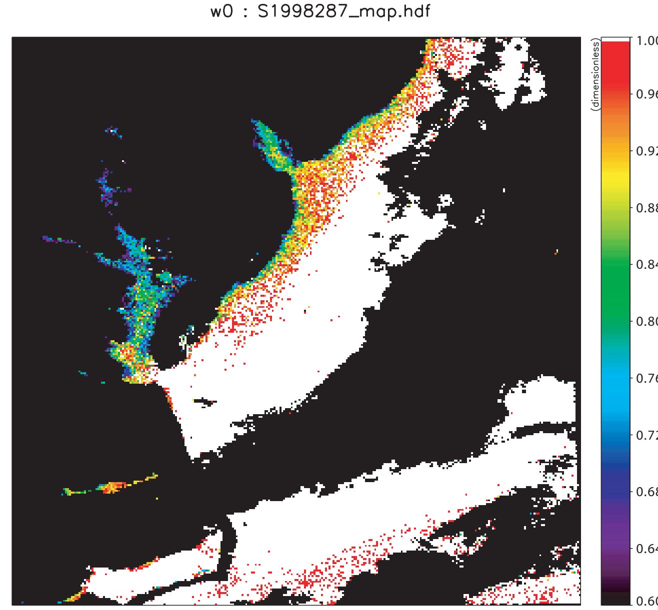

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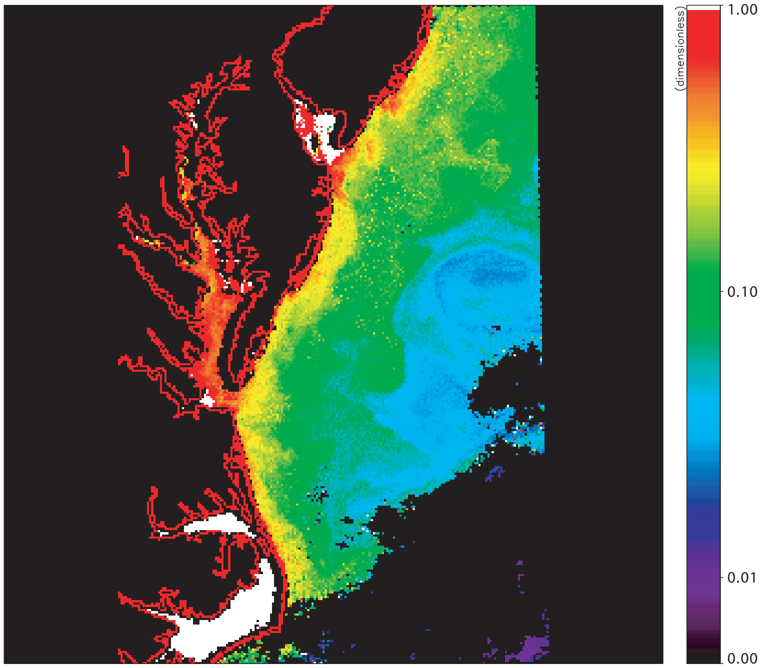

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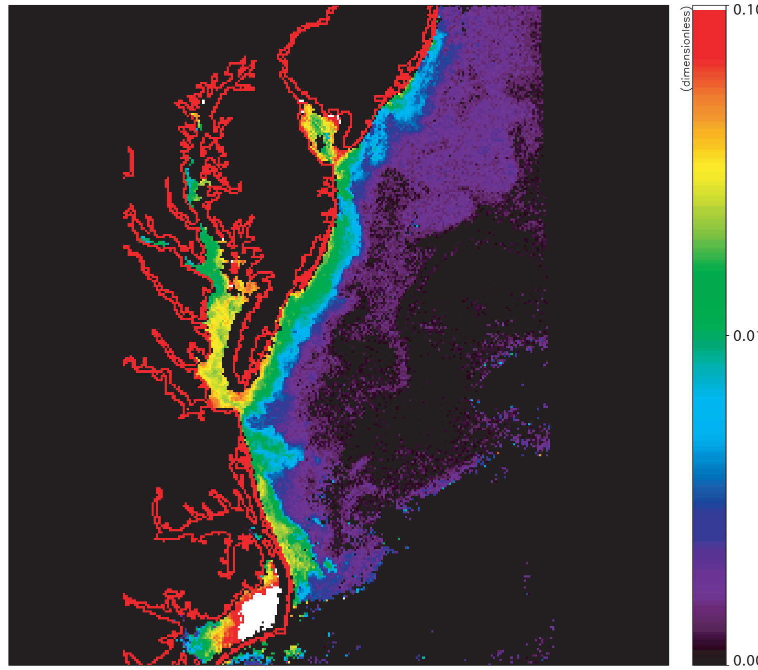

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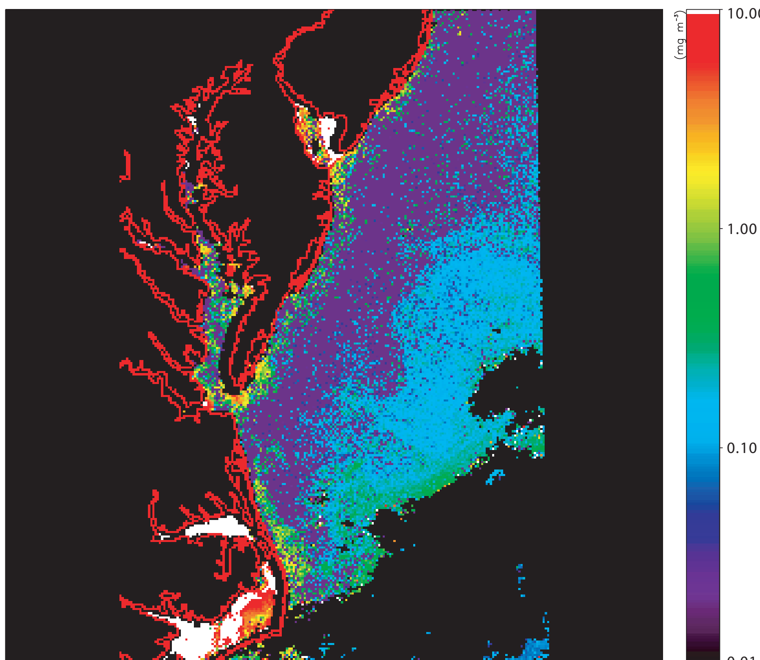

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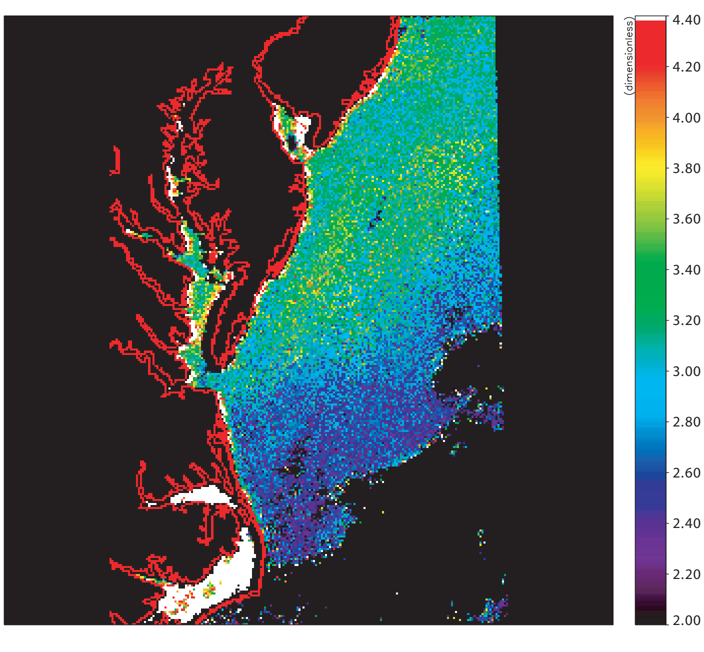

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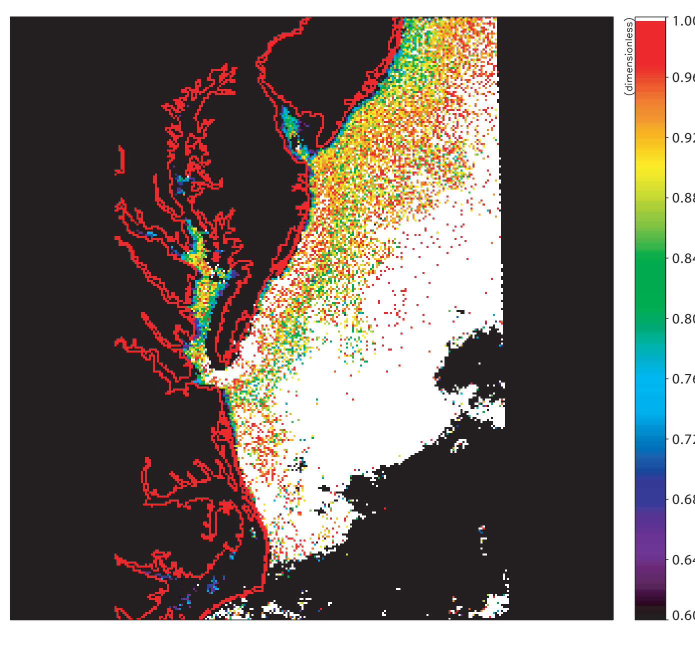

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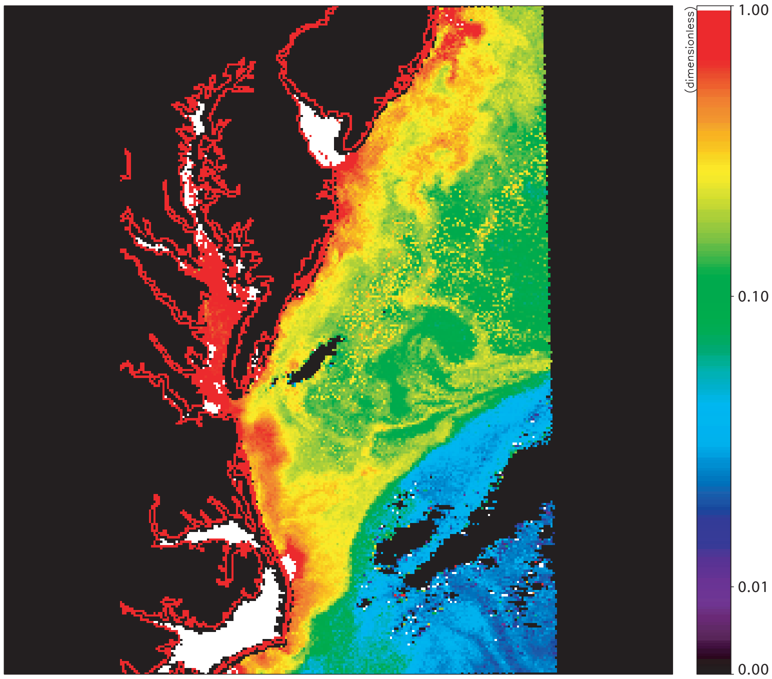

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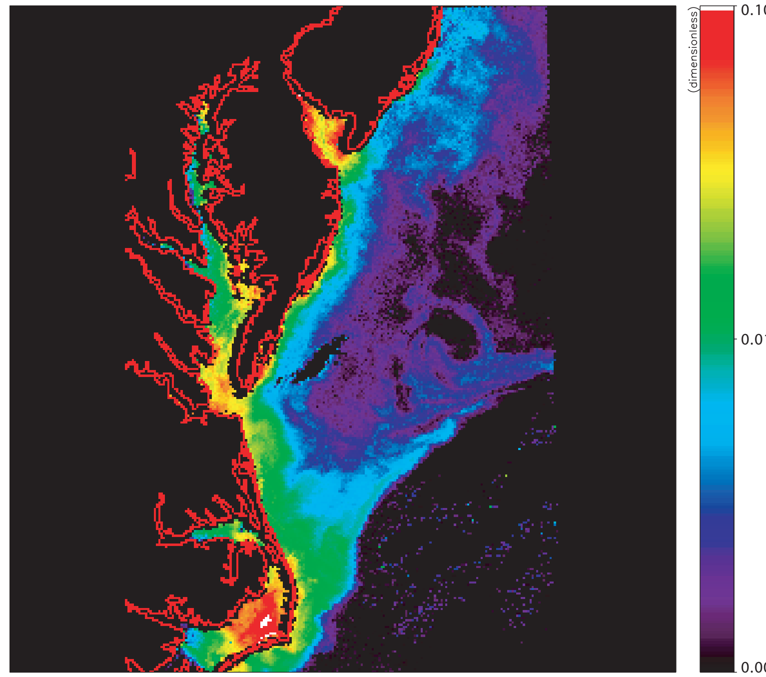

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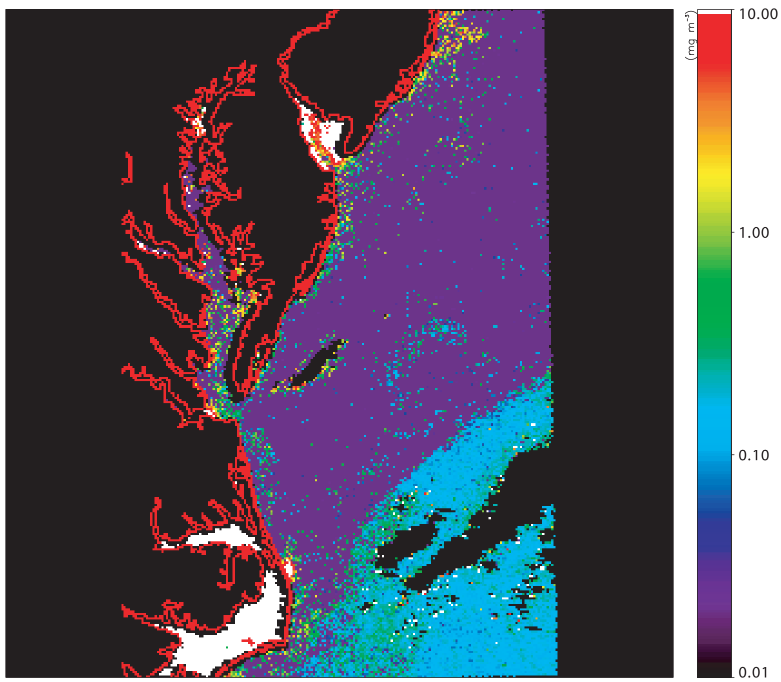

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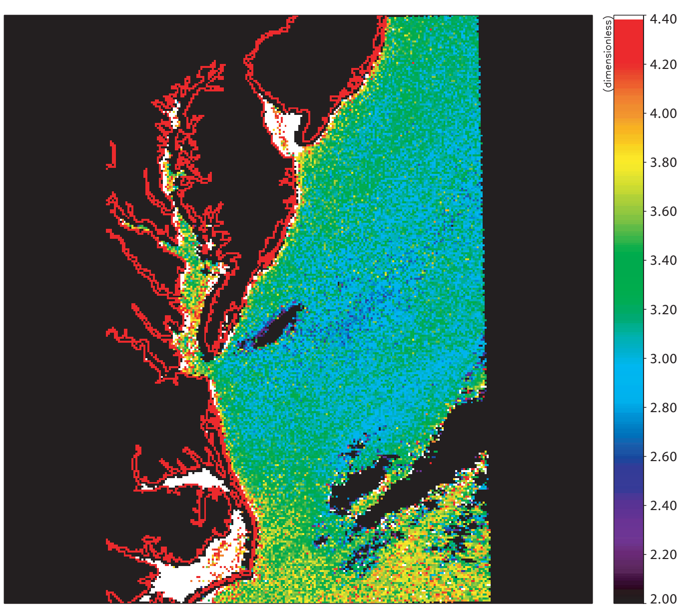

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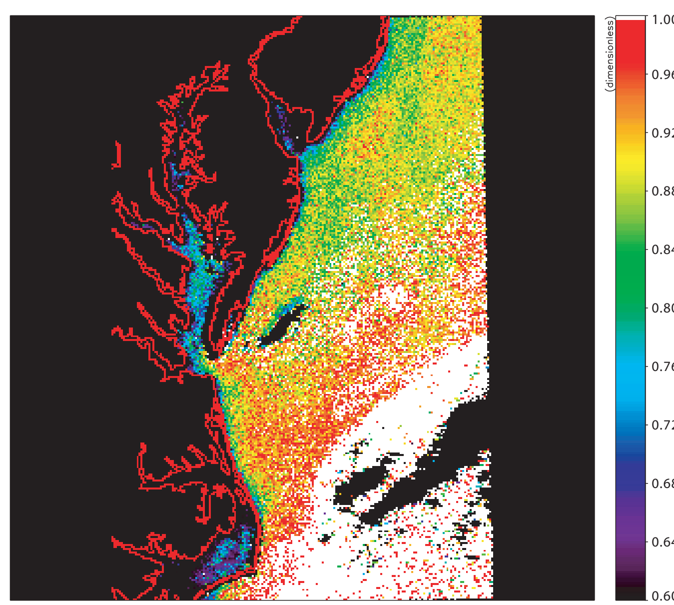

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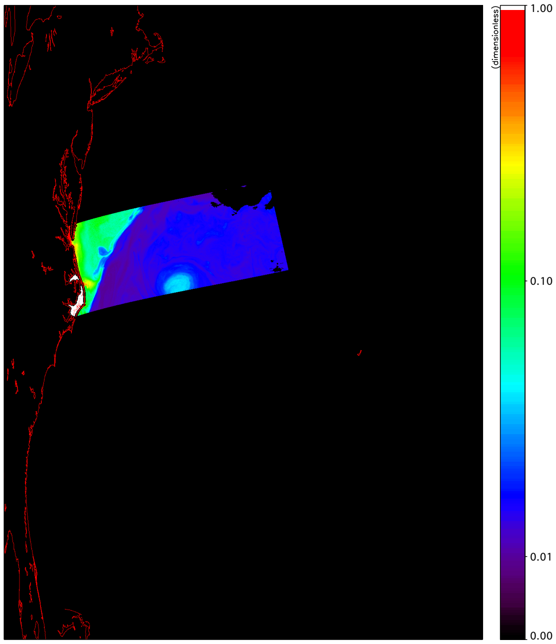

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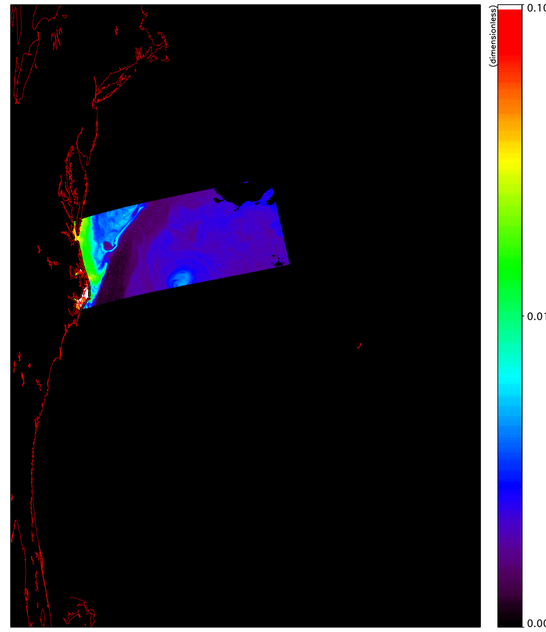

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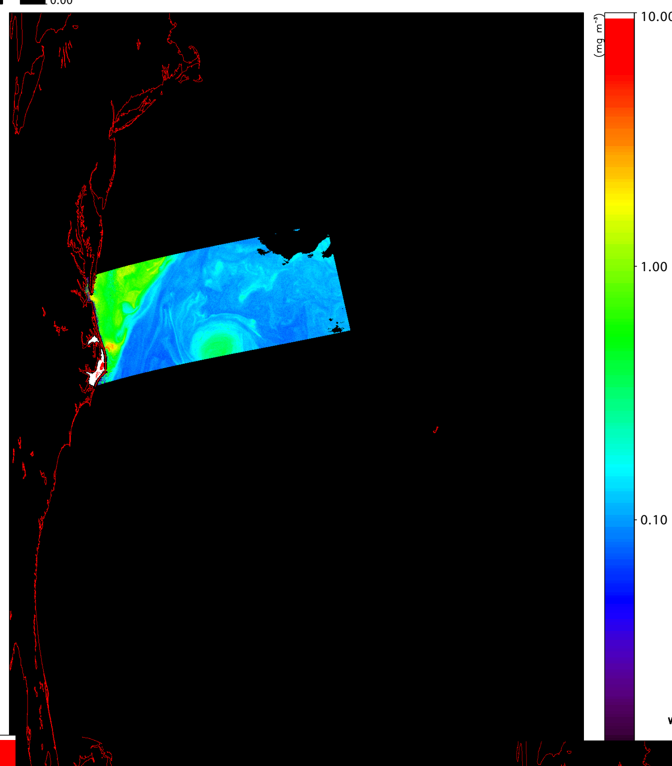

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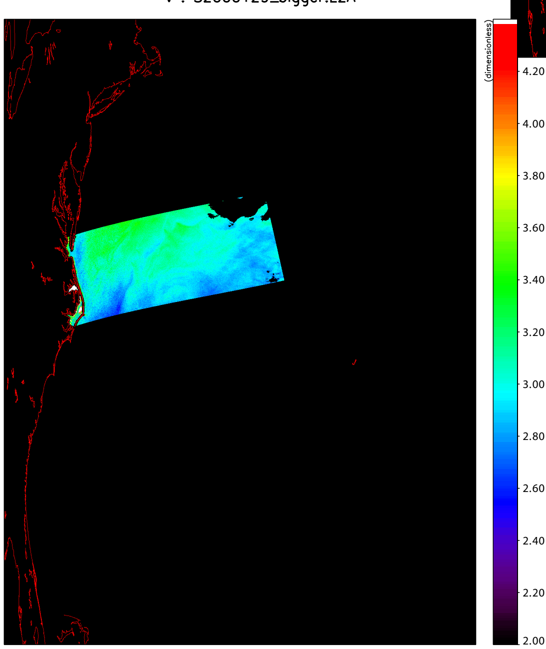

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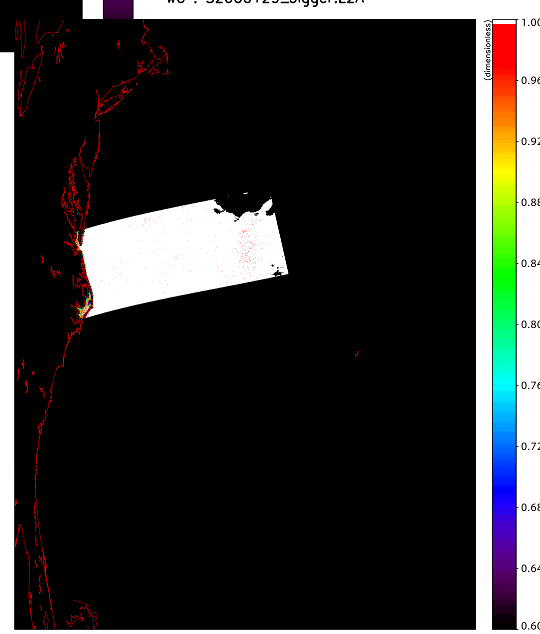

to be an excelling processing result no obvious failures and reasonable consistency in parameters.

Why does the algorithm display frequent failures in the coastal regime? There are several possibilities. First is that the actual water-leaving radiances in the blue are too small for the model to display any sensitivity to *C*, but note that a_{cdm} is retrieved in most situations. It may be that when a_{cdm}, and *C* are high, b_{bp} must also be high for a realistic retrieval. This seems born out by the fact that there is often an island (of higher b_{bp}) in regions of possible algorithm success in the midst of obvious failure. Second, the starting points for the optimization that were used for Case 1 waters may not be appropriate for Case 2 waters. The initial (and erroneous) assumption that $\_{w}$ = 0 in the NIR that is used before the first iteration, may drive the solution too far from reasonable values to allow a recovery. Third, the simple atmospheric model used in the SOA may not be sufficiently accurate to provide adequate recoveries of the small values of $\_{w}$ in the blue, which is critical for retrieval of *C*, but note that a_{cdm}. These and other possibilities are under study.

<u>Anticipated Future Actions</u>:

We are now making a major effort to explain this behavior of the Case 2 SOA in coastal waters, and provide a correction to the problem.

The subsurface upwelling BRDF

The subsurface BRDF issue involves relating measurements of the upwelled spectral radiance (used for bio-optical algorithm development, sensor calibration and product validation of all ocean color sensors) that are predominately made in the nadir-viewing direction (including MOBY data), with the water-leaving radiance at the remote sensor. The remote sensing viewing geometry is rarely nadir, thus an understanding of the difference of these two geometries is required, i.e., we need to understand the BRDF of the subsurface radiance distribution to reconcile these measurements. Our approach is to directly measure the BRDF as a function of the chlorophyll concentration and to develop a model that can be used for MODIS. In addition we are working on a specific algorithm for correcting the MOBY buoy data to address the BRDF effects at this location.

<u>Task progress:</u>
During this last period we have participated in several field experiments in Hawaii to collect radiance distribution data. When the satellite views the surface, it averages over a large area (approximately 1 sq km.). The instantaneous local upwelling radiance distribution is typically very noisy, due to wave focusing effects, thus we have to average a lot of data to simulate the satellite view of the ocean. The first of these two field experiments was an extended period of day cruises out of Honolulu. On these cruises the radiance distribution was measured along with other optical and physical properties of the water. These experiments were also directed towards getting more vicarious calibration data for the MODIS Aqua and Terra instruments. We have also spent time working on

reducing the data collected during this period and last, and we are starting to bring all of this data together to look at the BRDF in clear water.

Anticipated Future Actions:
We are currently working with Andre Morel on a paper describing our BRDF measurements in varied Chlorophyll environments, this will be finished by the end of the contract (May 15th). We have an additional short cruise in Febuary, collecting BRDF data and helping with the MOBY mooring and buoy exchange. We will also be bringing together all of our clear water data to develop the MOBY BRDF correction.

Validation of MODIS Algorithms and Products

4. Participate in MODIS Initialization/Validation Campaigns

This task refers to our participation in actual Terra/Aqua/MODIS validation/initialization exercises.

Task Progress:
We participated in two field exercises during the last 6 months, a MODIS/MOBY cruise in Hawaii during November, and we worked for several days on a small boat in Hawaii. The main portion of the MODIS/MOBY cruise was directed at swapping out the MOBY instrument, however we had expected to be able to collect more radiance distribution data during this cruise. In the end, however, the weather made it impossible to acquire data, as it was a period of high wind, and was fairly cloudy. We were able to accomplish the main goals of the cruise, the exchange of the MOBY instrument.
During the small boat cruise, over 500 radiance distribution data sets were collected, along with chlorophyll, and AC-9 data. This data was taken with the new optical redesign of the NuRADS system, which enables much better data to be obtained at larger nadir angles. We reduced all of the data from this cruise and the earlier cruises last spring, and we are now doing quality control and further analysis of the data.
We also participated in the MOBY reprocessing workshop during this period.

Anticipated future efforts:

Most of the work in the coming period will be spent analyzing the data obtained during our past field campaigns. This is the last period of the contract so we will be finalizing the data analysis for many of our data sets.

RETRIEVAL OF DETACHED COCCOLITH/CALCITE CONCENTRATION MOD 23

William M. Balch
Bigelow Laboratory for Ocean Sciences
POB 475
McKown Point
W. Boothbay Harbor, ME 04575

This last half year of work has focused on several areas: 1) processing of new Gulf of Maine validation samples for MODIS-Terra and MODIS-Aqua validation, 2) processing of data from our June '03 chalk-ex cruise aboard the *R/V Endeavor*, 3) submission of a manuscript on optics and hydrography of the Gulf of Maine (which includes material on acid-labile backscattering from PIC), 4) writing a new manuscript on the two-band MODIS calcite algorithm, validation, and new observations, 5) preparation of MODIS results for presentation at the Limnology and Oceanography meeting in Hawaii this coming February.

Algorithm Evaluation/Improvement

Task Progress:

We have continued performing measurements in the Gulf of Maine in order to assess the calcite-specific backscattering cross-section, an integral part of the two-band algorithm. Within the last 6 months, we have taken more validation data from the Gulf of Maine, specifically focusing on clear days. Those samples have been sent off for atomic absorption analysis and we are awaiting return of the data.

Validation of MODIS Algorithms and Products

As coccoliths and suspended PIC (particulate inorganic carbon or calcium carbonate) are new products, and as Terra was only launched in December 1999 and Aqua launched in May '02, there are relatively few data sets available for validation, particularly for the coccolith and suspended calcite products. This is because coccolith concentration (PIC) is not frequently measured at sea, while chlorophyll concentration is. In conjunction with our NASA SEAWiFS activities, much of our validation estimates come from the Gulf of Maine, the site of frequent blooms of coccolithophores, and a region readily accessible from our laboratory.

Validation of regional PIC

During 2003, we acquired 109 new PIC samples from our Gulf of Maine ferry studies. As mentioned above, these are being processed. Coccolith samples were taken at the same 109 stations, and those tedious microscope counts have been started during the last 6 months. Parallel PIC samples and coccolith counts have been taken in order to check the coccolith-to-carbon conversion, also important in the MODIS two band algorithm. We have demonstrated using previous data that satellite-derived normalized water-leaving radiances are statistically correlated to the absolute PIC concentration, accounting for as much as 40% of the variance. Moreover, the nLw's are even better correlated to the coccolith concentration; coccolith concentration accounts for just over 50% of the variance in nLw's in the blue and green wavelengths.

Chalk-Ex

Another aspect of algorithm validation was our June '03 Chalk-Ex experiment. For this experiment, we used Cretaceous coccolith chalk from the U.K. (with a median particle size identical to Emiliania huxleyi coccoliths) to make two patches, approximately 2 km x 1 km in size, which could be viewed by MODIS Terra or Aqua. The patches had sufficient calcite to provide concentrations equal to a typical bloom (but over negligible area as compared to typical coccolithophore blooms). During the last 6 months, we have focused on data processing, specifically on the Kriging techniques used to contour the calcite concentration (for the accuracy of the contouring programs is inherently important for defining the accuracy of the MODIS PIC algorithm). We have now optimized the contouring routine, and have focused on re-processing 3-D calcite information from the two patches, for comparison to the MODIS results. Given these optimization results, we will re-visit our Nov' 01 results and optimize them. Presentations on various aspects of this work were given November.

<u>New validation data</u>

Gulf of Maine cruises aboard the M/S *Scotia Prince* ferry resumed in early May of 2003 and ended in October 2003. Due to a very cloudy July, we lost two trips to overcast conditions, but our overall record for the season was 10 clear trips for validation out of 12 trips total.

<u>Validation of global PIC and coccolithophore pigment data</u>

Cautions when using coccolith/PIC data products

The coccolithophore data products are "provisionally validated", given that we have defined the RMS error based on ship validation measurements, under a wide range of PIC concentrations, using the collection 4 re-processed data. We nonetheless caution using these data from shallow ocean regions, particularly near carbonate banks (e.g. Grand Bahamas), where bottom reflectance will appear as a high-reflectance coccolithophore bloom (presumably such pixels would be flagged due to their shallowness). Moreover, near river mouths and in shallow waters, resuspended sediments (of non-calcite origin) may appear as high suspended calcite concentrations. Only use these data if the waters are sufficiently deep to not have such bottom resuspension or direct river impact. Beware that MODIS-derived coccolith concentrations assume that the coccoliths are from the Prymnesiophyte, *E. huxleyi*. If this is not true, then inaccuracies will increase although the errors are not expected to be large. Even when using the data in units of mg m^{-3}, they nevertheless assume a constant backscattering cross-section for *E. huxleyi*, which is known to vary with the size of the calcite particle.

Web Links to Relevant Information

The algorithm theoretical basis document for the coccolithophore products can be found at: http://modis.gsfc.nasa.gov/MODIS/ATBD/atbd_mod23.pdf

More information about the algorithm and inputs can be found in:

Esaias, W., et al., 1998, Overview of MODIS Capabilities for Ocean Science Observations, *IEEE Transactions on Geoscience and Remote Sensing*, **36**, 1250–1265.

<u>Anticipated future efforts</u>:
This is the last semi-annual report under this subcontract. Given that our MODIS re-compete proposal was funded, our future efforts will be:

4. Work-up of the results from the Gulf of Maine during 2003.

5. Continued sampling for PIC validation in the Gulf of Maine in '04 (12 more trips will be scheduled for clear-sky days)

6. Submission of the manuscript on the PIC algorithm and recent validation work

7. Any required revisions for our submitted paper on the Gulf of Maine results.

8. Processing of data from our June '03 Chalk-Ex experiment, specifically comparing the MODIS-derived results with the shipboard estimates of PIC concentration.

Referencing Data in Journal Articles

Results derived from this algorithm should cite the paper of Gordon et al.(Gordon et al. 1988) for the original discussion, and (Balch et al. 1996; Balch et al. 1999) for field data on the backscattering cross-section of calcite.

<u>Citations</u>

Balch, W. M., K. Kilpatrick, P. M. Holligan, D. Harbour, and E. Fernandez. 1996. The 1991 coccolithophore bloom in the central north Atlantic. II. Relating optics to coccolith concentration. Limnol. Oceanogr. **41:** 1684-1696.

Balch, W. M., D. T. Drapeau, T. L. Cucci, R. D. Vaillancourt, K. A. Kilpatrick, and J. J. Fritz. 1999. Optical backscattering by calcifying algae--Separating the contribution by particulate inorganic and organic carbon fractions. J. Geophys. Res. **104:** 1541-1558.

Gordon, H. R., O. B. Brown, R. H. Evans, J. W. Brown, R. C. Smith, K. S. Baker, and D. K. Clark. 1988. A semianalytic radiance model of ocean color. J. Geophys. Res. **93:** 10909-10924.

Additional Developments

(NAS5-31363 Personnel bold highlighted)

The following presentations were made during the previous half year:

Balch, W. M., Albert Plueddemann, Cindy Pilskaln- Bigelow Lab, Hans Dam, George McManus, Joaquim Goes. Chalk-Ex: Transport of optically active particles from the surface mixed layer. University of Rhode Island, November, 2003.

Voss, K. J.: BRDF of clear water, MOBY calibration/reprocessing meeting , November 20, Honolulu, Hi.

Publications (within last year):

(NAS5-31363 Personnel bold highlighted)

Balch WM and Drapeau DT (2004) Backscattering by Coccolithophorids and Coccoliths: Sample Preparation, Measurement and Analysis Protocols. In: Mueller JL, Fargion GS, McClain CR (eds) Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 5: Biogeochemical and Bio-Optical Measurements and Data Analysis Protocols. National Aeronautical and Space administration, Goddard Space Flight Space Center, Greenbelt, Maryland, pp 27-37

Balch, W. M. Re-evaluating the physiological ecology of coccolithophores. Chapter for: “COCCOLITHOPHORES - FROM MOLECULAR PROCESSES TO GLOBAL IMPACT”. Editors: Hans R. Thierstein and Jeremy R. Young. Springer-Verlag In revision June 2004. In Press.

V.F. Banzon, R.E. Evans, **H.R. Gordon** and **R.M. Chomko**, SeaWiFS observations of the Arabian Sea Southwest Monsoon bloom for the year 2000, *Deep Sea Research II*, (Accepted).

Broerse, A.T.C., Tyrrell, T., Young, J. R., Poulton, A. J., Merico, A. and **W. M. Balch**. 2003. The cause of bright waters in the Bering Sea in winter. **Continental and Shelf Research.** 23: 1579-1596.

C. Cattrall, K.L. Carder, K.T, and **H.R. Gordon**, Columnar aerosol single scattering albedo and phase function retrieved from sky radiance over the ocean: Measurements of Saharan dust, *J. Geophys. Res*., 108(D9), 4287, doi:10.1029/2002JD002497, 2003

R.M. Chomko, **H. R. Gordon**, S. Maritorena, D.A. Siegel, Simultaneous retrieval of oceanic and atmospheric parameters for ocean color imagery by spectral optimization: A validation, *Remote Sensing of Environment* **84,** 208—220, 2003.

H. Du and **K. J. Voss**, Effects of point spread function on calibration and radiometric accuracy of CCD camera, in press Applied Optics, December 2003.

H.R. Gordon, Comment on "Pitfalls in atmospheric correction of ocean color imagery: how should aerosol optical properties be computed?" *Applied Optics*, **42**, 542—544, 2003.

Vaillancourt, R.D., C.W. Brown, R.R.L. Guillard, **W. M. Balch**. 2003. Light backscattering by phytoplankton algae and a heterotrophic bacterium measured with a multi-wavelength, fixed-angle backscattering meter. In press. **J. Plankton Res.**.

Zhao, T. X. P., I Laszlo, B. N. Holben, C. Pietras, and **K. J. Voss**, "Validation of two-channel VIRS retrievals of aerosol optical thickness over ocean and quantitative evaluation of the impact from potential subpixel cloud contamination and surface wind effect, J Geophys. Res. 108(D3), 4106, doi:10.1029/2002JD002346, 2003.

OTHER WORKS SUBMITTED OR IN PREPARATION

Balch, W. M., D. Drapeau, B. Bowler, E. Booth, J. Goes, A. Ashe, and J. Frye. A multi-year record of optical properties in the Gulf of Maine: I. Spatial and temporal variability. Submitted to *Progress in Oceanography*.

Balch, W. M., D. Drapeau, B. Bowler, E. Booth, J. Goes, A. Ashe, and J. Frye. A multi-year record of optical properties in the Gulf of Maine: II. Connections between optics and hydrography. To be submitted to *Journal of Plankton Research*.

Esaias, W., M. R. Abbot, **W. M. Balch**, K. Carder, J. Campbell, D. Clark, R. Evans, H. R. Gordon, O. Brown, P. Minnett, E. Kearns, K. Kilpatrick, K. R. Turpie, R. Woodward, R. Vogel, and D. Thomas. 2003. Ocean primary production estimates from Terra MODIS and their dependency on satellite chlorophyll a algorithms. In Preparation.

Zhao, T. X. P, I. Laszlo, O. Dubovik, A. Smirnov, B. N. Holben, J. Sapper, D. Tanre, C. Pietras, **K. J. Voss**, and R. Frouin, Regional Evaluation of the Revised NOAA/NESDIS AVHRR Two-Channel Aerosol Retrieval Algorithm and Determination of the Refractive Index for Key Aerosol Types observed over the Ocean., Submitted to J. Geophys. Res..